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2008 Final Report on Grant N00014-04-1-0061: Microscopic Sources of Decoherence and Noise in Josephson Junction Qubits

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Executive Summary

The Josephson junction (JJ) qubit is a leading candidate in the design of a quantum computer. A significant advantage of this approach is scalability, as these qubits may be readily fabricated in large numbers using integrated-circuit technology. A major obstacle to the realization of quantum computers with Josephson junction qubits is decoherence. The goal of our research was to elucidate the microscopic sources of this decoherence and to suggest ways to eliminate or reduce these culprits. We focused on the decoherence produced by two level systems in the insulating barrier of a Josephson junction as well as in the insulating dielectric material (e.g., SiO_2) typically used to fabricate integrated circuit (IC) chips. Two level systems consist of an atom or group of atoms that can sit in one of two places. We worked with John Martinis' group (UCSB/NIST) which found that two level states are a dominant source of decoherence in superconducting qubits. One reason for this is that two level systems can resonantly absorb microwaves that are used to probe and manipulate the qubit. Once there are enough microwaves to saturate the two level systems, the rest of the microwaves can go through resulting in attenuation that decreases with increasing microwave power. Another mechanism for qubit decoherence is due to two level systems in the junction barrier which couple to the qubit. We explored two models in which a two level system couples to a qubit.

In the first model the two positions of an atom in a two level system correspond to two different values of the critical current. Since the energy splitting of the two states of a qubit depends on the value of the critical current, fluctuations of the two level system produces fluctuations in the energy splitting of the qubit and hence decoherence. Thus the qubit and two level system are coupled, and the strength of the coupling is proportional to the difference ΔI_o between the two values of the critical current. One way to monitor the quantum coherence of a qubit is to drive it with microwaves and observe the resulting Rabi oscillations that correspond to the qubit oscillating between its two states. We explored how two level systems lead to the decay of Rabi oscillations.

In the second model, which is more microscopic, a two level system is associated with an electric dipole moment. The voltage (or electric field) across the junction couples to this dipole moment, and hence to the qubit. In experimental scans of the qubit energy difference, this coupling manifests itself as avoided two-level crossings (splittings). We did a calculation that gives the distribution of these splittings that agrees well with the results of experiments done on Josephson junction phase qubits by John Martinis' group.

Why do two level systems affect the critical current? After all, a two level system consisting of a few atoms has a length scale of about 1 nm or less. This is orders of magnitude smaller than the 1 μm coherence length of a typical superconducting wavefunction. We showed that the answer is that the defect affects the tunneling barrier potential which enters into the exponent of the WKB tunneling matrix element T and hence can have a measurable effect on the critical current which goes as $|T|^2$. We checked this hypothesis by doing a microscopic calculation of the 1/f critical current noise as well as the 1/f charge noise due to two level systems in the insulating tunnel junction barrier. Our charge noise estimate agrees with experiment.

Our hope is that a microscopic understanding of decoherence can aid in the fabrication of better Josephson junctions and the realization of quantum computers.

2008 FINAL REPORT

Josephson junction (JJ) qubits are a leading candidate for making a quantum computer, with several experiments recently demonstrating single qubit preparation, manipulation, and measurement [1-4], as well as the coupling of qubits [5, 6]. A significant advantage of this approach is scalability, as these qubits may be readily fabricated in large numbers using integrated-circuit technology. A major obstacle to the realization of quantum computers with Josephson junction qubits is decoherence of the quantum mechanical wavefunction. The goal of our research was to elucidate the microscopic sources of this decoherence and to suggest ways to eliminate or reduce these culprits. We have been working closely with experimentalists, especially John Martinis (formerly at NIST, now at UC Santa Barbara), who is one of the leading investigators of this approach.

A simple way to make a qubit is with an rf SQUID which has one Josepshon junction. In this case the $|0\rangle$ and $|1\rangle$ states of the qubit are simply the lowest 2 states in the shallower potential well of the double well potential of the flux biased SQUID. The wavefunction ψ of the qubit is a coherent superposition of these two states:

$$\psi = \cos\frac{\theta}{2}|\,0\rangle + \sin\frac{\theta}{2}e^{i\phi}\,|\,1\rangle \tag{1}$$

The energy difference between these two states is $\hbar\omega_{10}$. Since $\hbar\omega_{10} \sim 9$ GHz ~ 450 mK and $T \sim 20$ mK, $\hbar\omega_{10} \gg kT$. So without any external pumping, the qubit will reside in its ground state.

Recent experimental evidence [7] obtained indicates that the dominant source of decoherence is two-level systems (TLS) in the insulating barrier as well as in the dielectric material, e.g., SiO_2, that is typically used as an insulator in the fabrication of integrated circuit chips. Two level systems have been used for years to describe the low energy excitations in amorphous materials at low temperatures (below 1 K) [8-11]. The microscopic nature of two level systems is still unknown. However, one can think of them as an atom or group of atoms that can sit in one of two positions. So think of a double well potential with an atom tunneling between the two positions. Two level systems in a dielectric material produce dielectric loss because they can resonantly absorb microwaves that are used to probe and manipulate the qubit. (In resonant absorption the energy (frequency) of the microwaves matches the energy splitting of the two level systems, so that a two level system is excited by absorbing an incoming microwave.) Once there are enough microwaves to saturate the two level systems, the rest of the microwaves can go through, resulting in attenuation that decreases with increasing microwave power. This has been known since the 1970's [12] and has been recently confirmed by the Martinis group. Superconducting qubits are nonlinear resonators formed by the Josephson inductance of the tunnel junction and its self-capacitance. The dielectric loss produced by the two level systems reduces the Q of the resonator. The realization of the problems caused by two level systems has prompted the Martinis' group to use less lossy dielectrics such as SiN that have fewer TLS, as well as to redesign qubits that require a smaller amount of insulating dielectric material. This has significantly increased the fidelity of the qubits and promises to increase the coherence time. (Higher fidelity means larger amplitude Rabi oscillations. See below.)

Two level systems residing in the insulating barrier of the tunnel junction can lead to decoherence by coupling to the qubit. We have been studying two models of this coupling. In the first model the fluctuations of two level systems in the insulating barrier of the JJ produce fluctuations in the critical current I_o [13]. Since the energy splitting of the qubit depends on I_o, a qubit can couple to a two level system. In the second model, which is more microscopic, the two level system is associated with an electric dipole moment. This dipole moment may be that of an OH^- impurity, or it may be due to an oxygen ion or an electron hopping between two positions. The voltage (or electric field) across the junction couples to this dipole moment, and hence to the qubit. Models 1 and 2 are related since a fluctuating charge can produce both a fluctuating dipole moment as well as fluctuations in the tunneling matrix element through the insulating barrier and hence, fluctuations in the critical current which is proportional to the square of the tunneling matrix element.

There is experimental evidence that a qubit can couple to a two level system with an energy splitting that is comparable to the energy splitting of the qubit. The energy splitting of the qubit can be tuned by changing the current bias. For most values of the current bias, the Martinis' group observes a single excitation frequency ω_{10}. However, at certain values of the current bias, they observe spurious resonances characterized by two closely spaced excitation frequencies [11]. To understand this, think of the four energy levels of the qubit-TLS system. Let $|g>$ and $|e>$ be the ground and excited eigenstates of the two level system. Then if there is no coupling between the qubit and TLS and if they have equal energy splittings, then the four states are the ground state $|0,g>$, the highest excited state $|1,e>$, and 2 degenerate states in the middle $|1,g>$ and $|0,e>$. If the qubit and TLS are coupled, then the degeneracy will be split by 2η where η is the strength of the coupling. We believe that this split degeneracy explains the pairs of closely spaced excitation frequencies seen experimentally by Martinis' group [13]. Furthermore experiment finds that the distribution of splittings goes as 1/S where S is the energy difference between the two closely spaced excitation frequencies. According to the explanation just given, the splitting $S=2\eta$. We have done a calculation that explains this distribution using the second model in which the dipole moment of the two level system couples to the electric field across the tunnel junction. (The electric field can come from microwaves or from oscillations of the qubit.) The calculation finds a cutoff for the distribution of splittings, and this cutoff agrees with that seen experimentally. This work was published in *Physical Review Letters* [7].

When the qubit is irradiated by microwaves that have a frequency ω_{10}, the qubit oscillates between the states $|0\rangle$ and $|1\rangle$. These oscillations are called Rabi oscillations. Let us take a moment to review Rabi oscillations [14]. Rabi oscillations occur if the qubit is irradiated with resonant microwaves whose frequency equals the qubit energy splitting. (Ignore the TLS for the moment.) If the qubit is initially in its ground state, the microwaves will initially increase the probability amplitude of finding the qubit in its excited state $|1\rangle$. However, as time goes on, at some point the qubit is completely in its excited state, and the electromagnetic wave goes on to de-excite the qubit through stimulated emission. So one sees oscillations in the probability P(1) of the qubit being in its excited state $|1>$. The frequency of the Rabi oscillations increases with the strength of the electric field.

One way to monitor the quantum coherence of the qubit is to drive it with microwaves and observe the resulting Rabi oscillations. Experiment finds that in the vicinity of the resonant splittings, the amplitude of the qubit's Rabi oscillations are reduced, implying that the coupling between the qubit and TLS is responsible for the reduction. We did calculations of a qubit coupled to a TLS in the presence of microwave driving. We explored two regimes where two level systems lead to the decay of Rabi oscillations. (A) We consider a Josephson qubit coupled resonantly to a two level system, i.e., the qubit and TLS have equal energy splittings. As a result of this resonant interaction, the occupation probability of the excited state of the qubit exhibits beating. Decoherence of the qubit results when the two level system decays from its excited state by emitting a phonon. (B) Fluctuations of the two level systems in the oxide barrier produce fluctuations and 1/f noise in the Josephson junction critical current. This in turn leads to fluctuations in the qubit energy splitting that degrades the qubit coherence. We compared our results with experiments on Josephson junction phase qubits. This work was published in Physical Review B [15].

More Recent Research

Background

We will now describe our more recent research efforts. Let us start with a brief review of the experimental measurements that have been done on 1/f noise in Josephson junctions and related devices. Wellstood has measured 1/f noise in DC SQUIDS at low temperatures (0.1 K to 5 K) and found that the noise power increases quadratically with temperature [16, 17]. (These SQUIDS had Nb-NbOx-PbIn junctions.) This temperature dependence has been something of a mystery [6] since one would expect that the noise at low temperatures would be due to two level systems that are predicted to give rise to noise with a linear temperature dependence due to thermal occupation factors [18, 19]. Kenyon, Lobb and Wellstood measured the temperature dependence of the charge noise power in two-junction Al-Al_2O_3-Al single-electron transistors at temperatures from 85 mK to 4 K [20]. They found that the charge noise was weakly temperature dependent below about 0.5 K, and increased with temperature above 1 K. They proposed a double well potential model in which a charge hops back and forth between the wells with two different hop rates. In this model the noise power has a quadratic temperature dependence. More recently Astafiev *et al.* [21] measured 1/f charge noise on a Josephson junction charge qubit consisting of a qubit island from which charge could jump on and off. They found that the noise power went as T^2 from 200 mK to about 1 K. The Delft group [22] studied low frequency resistance fluctuations in Al/AlO_x/Al (normal state) tunnel junctions. They found 1/f noise between 5 K and 300 K. Below 5 K one or two dominant individual two state fluctuators produced Lorentzian noise spectra. The temperature dependence of the noise spectral density was linear between 150 K and 1 K, and it saturated below 0.8 K. The cause of this saturation could be due to the quantum tunneling of fluctuators. Indeed Rogers and Buhrman [23] found temperature independent fluctuations below about 15 K in superconducting Nb-NbO-PbBi junctions. On the other hand, the low temperature saturation could be due to some other source of temperature independent noise that dominates the noise spectral density.

There has been recent theoretical work on two level systems as sources of decoherence in qubits. Shnirman *et al.* [24] used a model of two level systems that gives 1/f noise at low frequencies, and noise that increases linearly with frequency at high frequencies. (The high frequency behavior was seen by Astafiev *et al.* in charge qubits [25].) In addition the noise increased as T^2 as seen by Wellstood [16, 17] and Astafiev [21]. However, they had to assume that the density of states of two level systems increased linearly with energy. This disagrees with the flat density of states used in the standard model of two level systems that has been so successful in explaining the low temperature properties of glasses [11]. Faoro and Ioffe [26] have suggested that Kondo-like electron traps in the insulating Josephson junction barrier could account for low frequency 1/f noise that increases quadratically with temperature as well as high frequency noise that increases linearly with frequency. However, there is no evidence for magnetic Kondo impurities in the junction barriers. Faoro *et al.* [27] have suggested several models. In one, electrons hop between traps. In another Cooper pairs hop in and out of pairs of electron traps. In all their models they average over the traps and obtain a density of states that increases linearly with the energy.

Our Research

The critical current fluctuations ($\Delta I_o/I_o$) are often expressed in terms of $\Delta A/A$ where A is the area of the junction and ΔA is the effective area of the junction over which tunneling is blocked by a defect such as a two level system or a trapped charge [28]. Typically $\Delta A \sim 1$ nm^2 which is larger or comparable to the size of a two level system consisting of a few atoms. However, $\sqrt{\Delta A} \sim 1$ nm $\ll \xi$ where the superconducting coherence length $\xi \sim \hbar v_F/kT_c \sim 1\ \mu$m for a superconductor such as aluminum [29]. (v_F is the Fermi velocity.) ξ is the length scale over which the superconducting wavefunction varies. Why would such a small defect in the barrier affect the superconducting wavefunction whose length scale ξ is orders of magnitude larger? We showed that the answer is that the defect affects the tunneling barrier potential which enters into the exponent of the WKB tunneling matrix element T and hence can have a measurable effect on the critical current which goes as $|\mathrm{T}|^2$.

We checked this hypothesis by doing a microscopic calculation of the 1/f critical current noise due to two level systems in the insulating tunnel junction barrier. Suppose the oxide tunnel barrier without two level systems is represented by a square potential. Now consider a two level system that has an electric dipole moment $\vec{p}$. We calculated the electric potential of the dipole placed in the barrier between superconducting electrodes. The dipole modifies the barrier potential. We inserted this modified potential into a generalized WKB formula to calculate the change in the tunneling matrix element through the barrier [30-33]. We assumed that the dipole fluctuates by flipping 180^o, so this produces fluctuations in the tunneling matrix element. Squaring the tunneling matrix element gives the tunneling rate through the barrier, and from this we obtained the size of the fluctuations in the current density and hence in the critical current due to the fluctuating dipole. We then inserted the average critical current fluctuations $\langle(\delta I_o)^2\rangle$ into the formula for the noise power of a collection of two level systems [18] and averaged over the parameters of the standard two level system model to get 1/f critical current noise power. Once we had an expression for the critical current noise, we made a numerical estimate of its size which compared well with experiment. This work was published in 2007 in *Physical Review Letters* [34] after ONR funding had ended in 2006.

Given the magnitude and orientation of the dipole moment, we can calculate the charge noise due to charge induced on the electrodes by the fluctuating dipole. As described above, we can insert the charge fluctuations $\langle(\delta Q)^2\rangle$ into the formula for the noise power of a collection of two level systems [18] and average over the parameters of the standard two level system model to get 1/f charge noise. We have done this calculation for the charge noise. Our numerical estimate for the charge noise agrees well with experiment. We find that the noise power $S_Q/e^2 \sim 4.6 \times 10^{-4}$/Hz at a frequency of 1 Hz for a 1 μm^2 junction with two level systems that have dipole moments of 3.7 Debye which is the dipole moment of OH^- ions. Zorin *et al.* [35] find the charge noise power to be about 4×10^{-4}/Hz at a frequency of 1 Hz for a 1 μm^2 junction in an $Al/AlO_x/Al$ tunnel junction in a single electron transistor (SET). Zimmerli *et al.* [36] report the charge noise amplitude to be about $10^{-3}/\sqrt{Hz}$ for a 0.01 μm^2 $Al/AlO_x/Al$ junction at 10 Hz, which corresponds to a noise power of $10^{-4}/Hz$ at a frequency of 1 Hz in a junction with an area of 1 μm^2.

The charge noise is proportional to the dielectric loss tangent which is the ratio of the imaginary part of the dielectric constant to the real part of the dielectric constant. From our microscopic calculation we estimate the dielectric loss tangent to be 0.9×10^{-3} when the dipole moment is 3.7 Debye. This result is in good agreement with the experimentally measured loss tangent of 1.6×10^{-3} [7].

To summarize, our hope is that the improved understanding of microscopic sources of decoherence can lead to improved Josephson junction qubits and the realization of quantum computers.

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